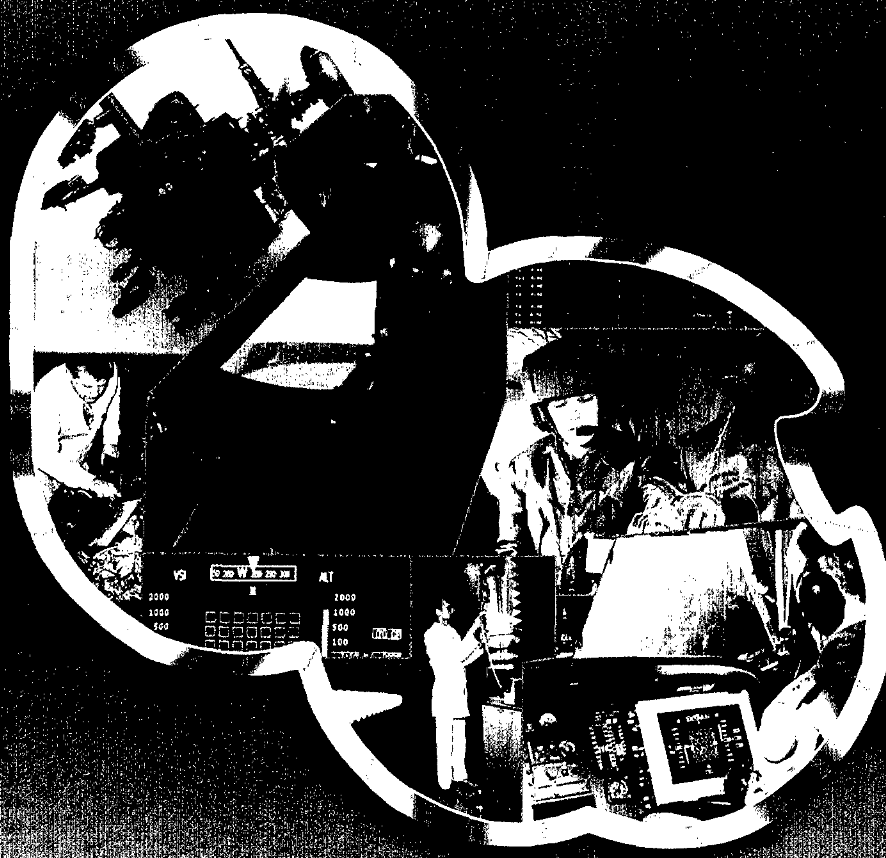
USAARL Report No. 2006-10

Accuracy, Repeatability and Instrument Myopia Induced by a Clinical Aberrometer – The Complete Ophthalmic Analysis System (COAS)



Aircrew Health and Performance Division

June 2006

USAARL

U.S. Army
Aeromedical Research
Laboratory

Notice

Qualified requesters

Qualified requesters may obtain copies from the Defense Technical Information Center (DTIC), 8725 John J. Kingman Road, Suite 0944, Fort Belvoir, Virginia 22060-6218. Orders will be expedited if placed through the librarian or other person designated to request documents from DTIC.

Change of address

Organizations receiving reports from the U.S. Army Aeromedical Research Laboratory on automatic mailing lists should confirm correct address when corresponding about laboratory reports.

Disposition

Destroy this document when it is no longer needed. Do not return it to the originator.

Disclaimer

Human use

Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRMC Reg 70-25 on Use of Volunteers in Research.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 2006	Final

4. TITLE AND SUBTITLE
Accuracy, Repeatability and Instrument Myopia Induced by a Clinical Aberrometer - the Complete Ophthalmic Analysis System (COAS)

5. FUNDING NUMBERS
PE-622787
PR-879
TA-P
WU-DA361539

6. AUTHOR(S)
Thomas O. Salmon, Corina van de Pol

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Aeromedical Research Laboratory
P.O. Box 620577
Fort Rucker, AL 36362-0577

8. PERFORMING ORGANIZATION REPORT NUMBER
2006-10

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Medical Research and Materiel Command
504 Scott Street
Fort Detrick, MD 21702-5012

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
Refractive surgery corrects lower-order refractive aberrations (sphere and astigmatism), but in many cases it inadvertently creates large higher-order aberrations that can degrade vision. This has prompted the development of new instruments, aberrometers, which measure higher-order aberrations. We evaluated a new clinical aberrometer, the Complete Ophthalmic Analysis System (COAS) for accuracy, repeatability and instrument myopia. Methods: We measured 56 normal eyes (28 subjects) using the COAS, with and without cycloplegia and evaluated its lower-order accuracy in comparison to clinical subjective refraction. We also evaluated lower- and higher-order repeatability and instrument myopia. Data were analyzed for a 5.0-mm diameter pupil. For comparison, some of these analyses were also performed on a conventional autorefractor. Results: Mean COAS accuracy for lower-order aberrations (sphere and astigmatism) was at least as good as clinical subjective refraction. Lower-order repeatability was similar to conventional autorefraction. For higher-order aberrations, repeatability, was in the 0.05-0.01-μm range (95% CI). Instrument myopia was small. Conclusions: On average, the COAS provides accurate, repeatable measurements of the lower-order aberrations (sphere and astigmatism) with little instrument myopia. We quantified repeatability for higher-order aberrations and provided recommendations on how to use the COAS in future refractive surgery-related research.

14. SUBJECT TERMS
aberrations, aberrometer, aberrometry, wavefront, refractive errors, accuracy, repeatability, instrument myopia, automated refraction

15. NUMBER OF PAGES
23

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

Acknowledgements

We would like to thank MAJ Linda Knapp Glisson, OD, and Jon B. Sawyer for their valuable assistance in collecting and processing data for this study.

Table of contents

Table of contents (continued)

List of tables

List of figures

Introduction

Refractive errors and higher-order aberrations of the eye

Until recently, the clinical measurement and correction of refractive errors was limited to just spherical and astigmatic errors, while additional more complicated refractive errors, known as higher-order aberrations, were ignored. For most normal patients, higher-order aberrations have little effect on vision, and until recently, they could not be measured or corrected clinically. This has changed with refractive surgery, which was originally designed to correct spherical and astigmatic errors. In many cases, the surgery inadvertently created large higher-order aberrations that caused uncorrectable poor vision (Howland, 2000, Maguire, 1994). These unwanted aberrations were particularly troublesome for patients with small treatment zones, higher prescriptions or large pupils (Boxer Wachler, 2003, Boxer Wachler, Huynh, El-Shiaty & Goldberg, 2002, Casson, 1996, Haw & Manche, 2001, Lee, Hu & Wang, 2003, Martínez, Applegate, Klyce, McDonald, Medina & Howland, 1998, Wachler, Durrie, Assil & Krueger, 1999). This also created concerns for Army aviation applicants. By regulation, these patients must have low spherical and astigmatic refractive errors but could have unrecognized large higher-order aberrations. Do higher-order aberrations adversely affect flight performance? Should the Army establish additional visual or optical standards for eyes that have had refractive surgery? How should higher-order aberrations be measured? What kind and magnitude of higher-order aberrations can be considered normal and abnormal? Because of refractive surgery, the formerly esoteric study of ocular aberrations became clinically relevant for eye care and aviation medicine.

Aberrometers—instruments that measure ocular aberrations

Higher-order aberrations are more difficult to measure than spherical or astigmatic refractive errors. In fact, until the recent development of aberrometers—instruments that measure higher-order aberrations—there was no clinical method available for measuring them.
In the 1970s engineers began to explore new techniques for measuring atmospheric aberration affecting telescopes. Dr. Roland Shack, of the University of Arizona, modified an old optical test, the Hartmann test, and invented what we now know as the Shack-Hartmann wavefront sensor (Platt & Shack, 2001). Shack-Hartmann sensors were fitted on the worlds' largest telescopes, and enabled astronomers to significantly improve telescope image quality (Fugate & Wild, 1994).

Dr. Junzhong Liang was the first person to use a Shack-Hartmann sensor to measure aberrations of the eye (Liang, Grimm, Goelz & Bille, 1994), and within a few years, other vision scientists around the world began using the same technique (Liang & Williams, 1997, Liang, Williams & Miller, 1997, Salmon & Thibos, 1998, Thibos & Hong, 1999, Miller, 2000, Moreno-Barriuso & Navarro, 2000, Hamam, 2000, Prieto, Vargas-Martin, Goelz & Artal, 2000, Hofer, Artal, Singer, Aragon & Williams, 2001, Porter, Guirao, Cox & Williams, 2001, Marcos, Diaz-Santana, Llorente & Dainty, 2002, Thibos, Hong, Bradley & Cheng, 2002, Yoon & Williams, 2002, Salmon, West, Gasser & Kenmore, 2003). Although other technologies have been developed to measure the eye's higher-order aberrations, Shack-Hartmann-type aberrometers are the most popular. In 2001, WaveFront Science, Inc, (Albuquerque, NM) began marketing the

Complete Ophthalmic Analysis System or COAS (Figure 1), which was the first commercial ophthalmic Shack-Hartmann aberrometer.

Clinically, refractive errors are usually measured by a nulling technique that determines the spherical and astigmatic lenses needed to negate the errors. Aberrometers, on the other hand, measure distortions in wavefronts of light that have passed through the eye's optics; that is, they directly measure the optical errors, and they do so my measuring the topography of a wavefront of light at many locations across the pupil (Salmon & West, 2002). To do this, Shack-Hartmann aberrometers project light onto the eye, and then measuring the light reflected back out of the eye (Figure 2a). While an aberration-free eye will emit a wavefront with perfectly flat topography, aberrations in the eye's optical system will bend or warp the wavefront. Depending on the kind of refractive aberrations present, the wavefront can be distorted into various, sometimes complex, shapes. Figure 2b illustrates a wavefront that has been curved by a myopic refractive error.

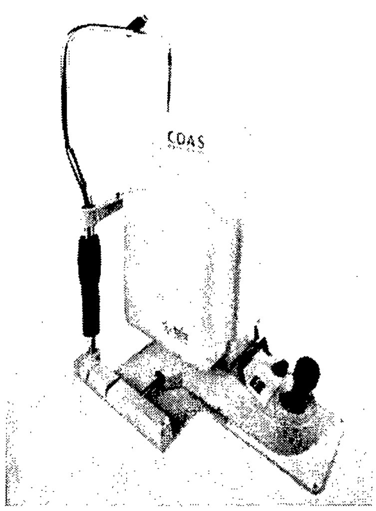


Figure 1. The Complete Ophthalmic Analysis System (COAS).

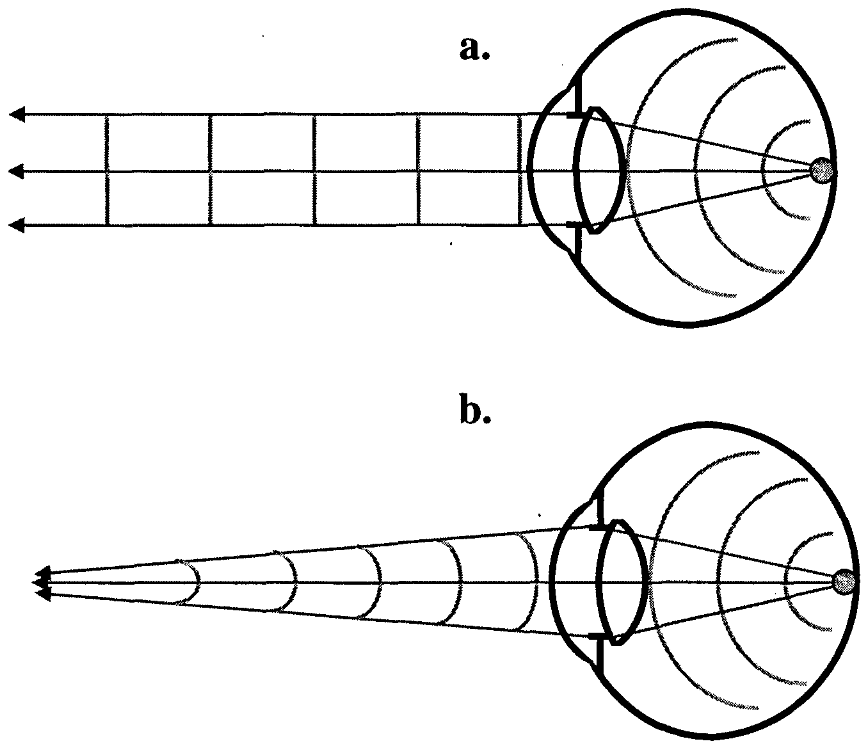


Figure 2. How Shack-Hartmann aberrometers measure wavefront errors. Shack-Hartmann aberrometers projecting a point onto the retina and measure the wavefront of light emitted from the eye. In an eye with perfect optics, a flat wavefront emerges (a). Aberrations such as simple myopia (b) bend and distort the wavefront.

Reporting aberrations—Zernike polynomials

Conventional clinical notation reports refractive errors using three numbers—the sphere, cylinder and axis (for astigmatism) of the correcting lens, while higher-order aberrations are ignored. A new notation was needed that could include the higher-order refractive errors (aberrations), and in 2000, the Optical Society of America (OSA) adopted Zernike polynomials as the standard system for specifying aberrations of the eye (Atchison, Scott & Cox, 2000, Thibos, Applegate, Schwiegerling, Webb & Members, 2000). The OSA standard is now well established internationally among refractive surgeons and vision scientists. Zernike polynomials break down the eye's refractive error into well-defined sub-aberrations, known as Zernike modes; that is, each mode is a distinct type of refractive error or aberration. This system identifies modes using either a single-number index (which is more convenient for graphing), or a double index that uses a subscript and superscript. Depending on the detail required, any number of Zernike modes may be included in the analysis of an eye's total refractive error. Some papers have described refractive errors analyzed into as many as 65 modes (Liang & Williams, 1997; Liang et al., 1997; Salmon, 1999). The Zernike modes may be grouped into a hierarchy of orders, which contain refractive aberrations of increasing complexity. When the

OSA subscript-superscript notation is used, the subscript indicates the Zernike order, while the superscript identifies a specific aberration within that order. For example, Z_3^{-1} represents the third-order aberration, which is sometimes called vertical coma (Atchison et al., 2000).

Study objectives

The United States Army Aeromedical Research Laboratory (USAARL) is evaluating refractive surgery and its impact on Army pilots. Instrumentation that can accurately measure the optics of the human eye is needed to objectively evaluate optical and visual performance. The objectives of this study were to evaluate the Complete Ophthalmic Analysis System (COAS; manufactured by Wavefront Sciences, Inc., Albuquerque, NM) in terms of its 1) accuracy, 2) repeatability and 3) induced instrument myopia for a normal population of Army flight school applicants who had not undergone refractive surgery.

Accuracy, sometimes called validity, describes how correctly an instrument measures what it is supposed to measure. We evaluated accuracy for spherical defocus and astigmatism only, by comparing COAS measurements to data obtained using standard clinical methods. We were not able to assess accuracy for higher-order aberrations because we had no other way to measure the higher-order aberrations than by using the COAS aberrometer.

Repeatability describes measurement consistency. We assessed repeatability for both lower (sphere and astigmatism) and higher-order aberrations by making multiple measurements and computing the variance. We also measured instrument myopia, which it is the tendency of the eye to over-focus when looking into tabletop instruments such as the COAS. This and other automated refractors contain an internal fixation target that is optically projected to infinity, so the eye will focus at that distance. However, in spite of the fact that the target is at infinity optically, some eyes focus for a nearer distance because the patient knows the object he's viewing is actually near (inside the instrument). This contributes to measurement error because it makes the instrument over-estimate myopia or underestimate hyperopia.

The principles of Shack-Hartmann aberrometry are well established and laboratory devices have proven reliable (Moreno-Barriuso & Navarro, 2000, Prieto et al., 2000, Salmon & Thibos, 1998). However, apart from information provided by the manufacturer, little work has been done to test accuracy of the new clinical aberrometers, including the COAS. One recent study reported the accuracy, repeatability and instrument myopia of the COAS for measurements of spherical defocus and astigmatism for a group of twenty myopic patients (Salmon et al., 2003). Table 1 summarizes the COAS's accuracy reported in that study. It shows measurement error, in diopters (D) for pupil diameters of 4.0 and 6.7 mm, as well as accuracy for a conventional autorefractor. Table 2 shows lower-order repeatability reported in the same study for the COAS and autorefractor, without and with cycloplegia. COAS Instrument myopia was reported to be –0.03 D, better than that for the autorefractor, which was –0.21 D.

Table 1.
Previously reported accuracy for the COAS for the sphere and astigmatism (Salmon et al., 2003).

	Without cycloplegia (D)				With cycloplegia (D)			
Instrument	Pupil	Sphere	Cylinder	Vector	Pupil	Sphere	Cylinder	Vector
COAS	4.0	0.00	-0.20	+0.33	4.0	+0.07	-0.19	+0.32
	6.7	+0.19	-0.23	+0.37	7.7	+0.19	-0.15	+0.41
Autorefractor	3.5	-0.02	-0.20	+0.34	3.5	+0.16	-0.17	+0.22

Table 2.
Previously reported repeatability for the COAS (Salmon et al., 2003).

Instrument/pupil size	Without cycloplegia (D)	With cycloplegia (D)
COAS 4-mm pupil	0.27	0.16
COAS full pupil	0.24	0.12
Autorefractor 3.5-mm pupil	0.31	0.19

Methods

Subjects

We recruited 28 volunteers from among pilot candidates who were undergoing a Class I physical examination, as required for entry into flight school. Inclusion criteria were the same as the vision and ocular health requirements to enter flight school in accordance with AR 40-501. These included

- Refractive error between –0.75 D of myopia and +3.00 D of hyperopia, and ≤ 0.75 D of astigmatism.
- Uncorrected visual acuity of 20/50 or better in each eye.
- Best corrected visual acuity of 20/20 or better in each eye.
- No evidence of ocular disease

In addition, subjects must not have worn rigid contact lenses within 6 months, never have had refractive surgery, and have no medical contraindications to the use of cycloplegic or anesthetic eye drops. Our sample included one female, and 27 male subjects, with a mean age ±standard deviation of 24.7 ±3.3 years. The mean non-cycloplegic refractive error was, +0.30 ±0.41 D sphere and –0.21 ±0.26 D cylinder. Cycloplegia shifted the mean spherical refractive to +0.41 ±0.70 D.

Procedures

The protocol was approved beforehand by the US Army Aeromedical Research Laboratory (USAARL) Human Use committee. Each subject provided written informed consent before participating. One of the tests required by the Class I flight physical is a measurement of the

refractive error with cycloplegia. Cycloplegic eye drops are instilled to temporarily paralyze the eye's near-focusing mechanism, and thereby ensure more accurate measurements. For the purposes of this study, several additional tests were added to each subject's flight physical. We performed the following tests, in the following order, on each subject's right and left eye.

1) Measurement of refractive errors <u>without</u> cycloplegia
   a. Autorefraction using the Nidek ARK-700A, a commonly-used clinical instrument that objectively estimate the spherical and astigmatic errors only
   b. Conventional clinical subjective measurement of the spherical and astigmatic refractive errors by an optometrist
   c. COAS measurements of sphere, astigmatism and higher-order aberrations
2) Measurement of refractive errors <u>with</u> cycloplegia
   a. COAS measurements of sphere, astigmatism and higher-order aberrations
   b. Clinical subjective measurement of the spherical and astigmatic refractive errors by an optometrist
   c. Autorefraction using the Nidek ARK-700A

For the COAS measurements, the subject placed his head on a chin rest and stared at a fixation pattern inside the machine, while the operator aligned his eye on a video monitor, and took five measurements within about one minute. The COAS was configured to report the refractive error for a 5-mm diameter pupil, and analyze aberrations up to the eighth Zernike order (44 modes). All measurements were made with dim room illumination. After each measurement, the COAS data, including sphere, cylinder, axis, pupil diameter, Zernike coefficients and other information were saved to a database for later analysis.

Analysis of accuracy

Ideally, when evaluating accuracy of an instrument, the true value to be measured should be known. For example, in an earlier USAARL study of videokeratoscope accuracy, we compared the known dimensions of plastic artificial corneas to the measurements reported by the instrument (Salmon, Rash, Mora & Reynolds, 2002). An absolute test of the aberrometer's accuracy is not possible because there is no means to exactly know the true value of each eye's aberrations. Clinical subjective refraction provides our best estimate of lower-order aberrations (sphere and astigmatism) but it does not measure higher-order aberrations. Accuracy testing was therefore limited to lower-order aberrations (sphere and cylinder). We compared sphere and cylinder measured by the COAS with the clinical refraction for each eye. Since clinical subjective refraction, our gold standard, is accurate to only within ±0.25 D, our assessment of COAS accurate could not be better than this. COAS accuracy was expressed as the presumed error, that is, the difference between the COAS and clinically determined values for the sphere and astigmatism.

We processed the refraction data (sphere, cylinder and axis for each eye) according to the following steps (Salmon et al., 2003).

1) Convert sphere, cylinder and axis to power vectors.

The standard clinical notation for recording refractive errors (sphere, cylinder and axis) is not well suited to statistical analysis, since it does not allow the direct computation of differences, means or variances. Therefore we transformed sphere (S), cylinder (C) and axis (θ) into three quantities, referred to as J_{45}, M and J_{180}, according to Eqs. (1-3). These constitute the components of a vector that allows statistical analysis (Thibos, Wheeler & Horner, 1997). All subjective refraction data were treated in this way. The subjective refraction for each eye was converted to a vector quantity labeled vector S.

$$J_{45} = (-C/2)\sin(2\theta) \tag{1}$$

$$M = S + C/2 \tag{2}$$

$$J_{180} = (-C/2)\cos(2\theta) \tag{3}$$

2) Five COAS measurements were made of each eye, and these measurements were likewise converted to dioptric power vectors (by Eqs (1-3), above). We computed the mean J_{45}, M and J_{180}, of the five measurements (mean COAS power vector) for the mean COAS refraction for each eye. This vector quantity was labeled vector C.
3) COAS *error* was defined as the difference (vector E) between the COAS (vector C) and subjective refractions (vector S), according to Equation 4.

$$\vec{E} = \vec{C} - \vec{S} \tag{4}$$

4) Finally we computed the overall mean COAS error by averaging vector E across all eyes. To simplify interpretation, we converted this vector quantity back to the clinical notation using sphere, cylinder and axis by Eqs. (5-7).

$$C = -2\sqrt{J_{45}^2 + J_{180}^2} \tag{5}$$

$$S = M - C/2 \tag{6}$$

$$\theta = [\tan^{-1}(J_{45}/J_{180})]/2 \tag{7}$$

To ensure that the axis computed by Equation 7 conformed to standard clinical minus-cylinder notation ($0>\theta\geq180$ degrees), we corrected the axis value based on the initial result for θ (Equation 7) and the logical tests below.

IF $J_{180} < 0$, axis = $\theta+90$
IF $J_{180} = 0$ AND IF $J_{45} < 0$, axis = 135
IF $J_{180} = 0$ AND IF $J_{45} > 0$, axis = 45
IF $J_{180} > 0$ AND IF $J_{45} \leq 0$, axis = $\theta+180$
IF $J_{180} > 0$ AND IF $J_{45} > 0$, axis = θ

5) We also computed the magnitude (m) of the COAS error vector (vector E, above) for each eye, according to Equation 8, where J_{45}, M and J_{180} were components of vector E. This simplified interpretation by converting the three-number vector quantity E to a single-number metric, magnitude m. We then computed the mean magnitude of these errors across eyes.

$$m = \sqrt{J_{45}^2 + M^2 + J_{180}^2} \tag{8}$$

The default/standard COAS computation of spherical refractive power is based on the value of mode Z_2^0 (defocus) only, but the COAS offers an alternate computation referred to as the "Seidel sphere." This includes mode Z_4^0 (spherical aberration) in the calculation, and may better match the way a human eye responds to a subjective refraction. A complete description of how the COAS computes both the standard and Seidel spheres may be found in another article (Salmon et al., 2003). We tested COAS accuracy for both the standard and the Seidel sphere. For comparison, we also tested accuracy of the autorefractor by following same procedures for three autorefractor measurements of each eye. Accuracy was analyzed separately for right and left eyes with and without cycloplegia.

Repeatability for lower-order aberrations

We evaluated COAS repeatability for the lower-order aberrations (sphere and astigmatism) and higher-order aberration separately. For each eye (right and left) and condition (without and with cycloplegia), five measurements with the COAS were taken within about one minute. We analyzed repeatability for sphere and astigmatism using both the standard and Seidel sphere powers. Autorefractor repeatability was computed in the same manner, except that only three autorefractor measurements were taken of each eye. We processed lower-order data for each eye as follows.

1) Convert each of the five COAS refractions (sphere, cylinder, axis) to a power vector (Equations 1-3).
2) Compute the mean COAS refraction as the mean of the five original power vectors.
3) Subtract the mean from each of the five original power vectors. This gave five difference vectors.
4) Compute the magnitude (Equation 8) of each difference vector and the mean of these five magnitudes. This gave the mean deviation, in diopters (D), for each eye.
5) Square and sum the mean deviations for 28 eyes and divide by 28 to obtain the RMS (root mean squared) deviation.
6) Compute a repeatability coefficient, defined as the RMS deviation multiplied by 1.96. This analysis generally follows the methods described by Bland and Altman (1986) and used in other clinical studies to evaluate repeatability of diagnostic instruments (Rosenfield & Chiu, 1995, Walline, Kinney, Zadnik & Mutti, 1999, Zadnik, Mutti & Adams, 1992).

Repeatability for higher-order aberrations

Higher-order aberrations (Zernike Orders 3-8 containing Modes 6-44 or Z_3^{-3} through Z_8^{8}) have no clinically familiar nomenclature, so we performed repeatability statistics directly on their Zernike coefficients. Five COAS measurements were made of each eye/condition and this yielded five strings of 39 Zernike coefficients. We computed a standard deviation, standard error and finally a 95% confidence interval for each mode, and then averaged the confidence intervals across 28 eyes. The mean 95% confidence intervals for each mode were interpreted as a measure of instrument noise and repeatability for higher-order aberration. This process was applied separately to right and left eyes, without and with cycloplegia.

Instrument myopia

We computed instrument myopia for the COAS and the autorefractor in the following steps.

1) Cycloplegia could have induced a slight change in the true refractive error, so for each eye, we computed any such change (vector Δ) as the difference between the subjective non-cycloplegic (vector S_m) and subjective cycloplegic (vector S_c) power vectors Equation 13.

$$\vec{\Delta} = \vec{S}_m - \vec{S}_c \tag{13}$$

2) Instrument myopia, vector I in Equation 14, for each eye was defined as the difference between the COAS non-cycloplegic (vector C_m) and COAS cycloplegic (vector C_c) refractions minus the true change, vector Δ from Equation 13.

$$\vec{I} = \vec{C}_m - \vec{C}_c - \vec{\Delta} \tag{14}$$

The mean of all COAS instrument myopia values was computed for right and left eyes when the standard and Seidel sphere values were used. Mean instrument myopia power vectors were converted to sphere, cylinder and axis and the mean spherical equivalent power.

Results

Accuracy

Table 3 summarizes the statistics for COAS accuracy for spherical and astigmatic (cylinder) refractive error. For comparison, Table 4 summarizes accuracy for the autorefractor.
The magnitude of the mean error vector (Table 3, right column) provides a single-number metric to judge COAS overall accuracy for measuring spherical plus astigmatic refractive error. For all eyes and conditions the error was less than 0.5 D, which is similar to the range of error seen with the autorefractor (Table 4). Smallest COAS error was found when cycloplegia was used, without the Seidel option (vector error about 0.3 D). Otherwise, without cycloplegia, power vector error using either the standard or Seidel power was about 0.4 D.

Table 3.
COAS lower-order accuracy.

Eye/condition	Sphere method	Mean sph error	Mean cyl error	Mag vector error
OD/no cyclo	Standard	-0.10 ±0.60	-0.09 ±0.27	0.43 ±0.25
OS/no cyclo	Standard	-0.14 ±0.64	-0.07 ±0.34	0.43 ±0.30
OD/no cyclo	Seidel	+0.08 ±0.55	-0.09 ±0.27	0.38 ±0.22
OS/no cyclo	Seidel	+0.08 ±0.64	-0.07 ±0.34	0.43 ±0.24
OD/cyclo	Standard	+0.14 ±0.42	-0.08 ±0.31	0.29 ±0.14
OS/cyclo	Standard	+0.11 ±0.46	-0.09 ±0.32	0.29 ±0.20
OD/cyclo	Seidel	+0.44 ±0.42	-0.08 ±0.30	0.45 ±0.24
OS/cyclo	Seidel	+0.41 ±0.40	-0.09 ±0.32	0.41 ±0.22

Note: The table shows accuracy for measuring sphere and astigmatic refractive error for right (OD) and left (OS) eyes, without and with cycloplegia, using the standard or Seidel option for spherical power. Values are in diopters (D) plus or minus one standard deviation. A negative value for the mean spherical error shows that the instrument overestimated myopia. A positive error indicates that it overestimated hyperopia. The last column shows the magnitude of the error when expressed as a power vector. COAS analysis pupil diameter was 5.0 mm.

Table 4.
Autorefractor accuracy.

Eye/condition	Sphere error (D)	Cylinder error (D)	Vector magnitude (D)
OD/no cyclo	+0.29	-0.15	**0.40**
OS/no cyclo	+0.28	-0.12	**0.41**
OD/cyclo	+0.46	-0.09	**0.47**
OS/cyclo	+0.43	-0.05	**0.47**

Note: A negative sphere error indicates the instrument overestimated myopia; a positive error indicates hyperopic error. The last column shows the mean error in terms of power vector magnitude (bold). The autorefractor measured across a 3.5-mm diameter pupil.

For all eyes and conditions, mean cylinder error was less than -0.1 D. Without cycloplegia, the COAS standard sphere tended to overestimate myopia by about -0.1 D. Cycloplegia shifted the mean error for standard sphere to about +0.1. In general the Seidel option shifted the mean spherical error about +0.25 D for a 5.0-mm diameter pupil. Poorest accuracy for the sphere power was seen when the Seidel option was used with cycloplegia.

Figure 3 shows the distribution of COAS vector errors across a range of spherical refractive errors (right and left, standard and Seidel spheres) when no cycloplegia was used. For both the standard sphere (black symbols) and Seidel sphere (white symbols), approximately 80% of the

errors were less than 0.60 D. In a few cases the vector error exceeded 1.00 D. The Seidel sphere resulted in fewer extreme errors, so that none exceeded 0.90 D.

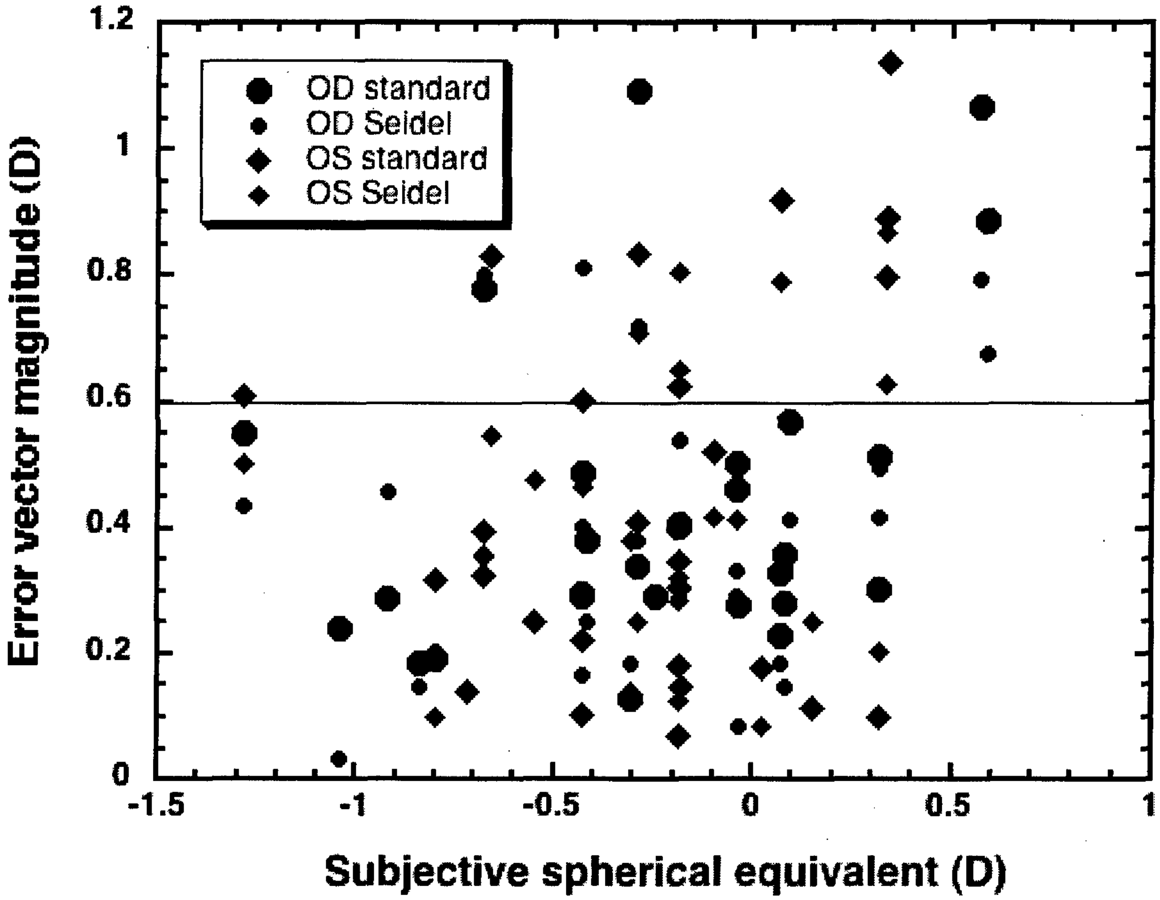


Figure 3. Distribution of COAS refractive vector errors (without cycloplegia). Approximately 80% of the errors, using both the standard (large symbols) and Seidel spheres (small symbols) are within 0.60 D.

Figure 4 shows a similar plot when cycloplegia was used. The distribution of errors was concentrated closer to zero, with approximately 90% of the errors less than 0.60 D. In this case, fewer outliers were seen when the standard sphere, rather than Seidel sphere was used. In both Figures 3 and 4, the larger errors are on the right side of the distributions, that is, for eyes with very low myopia or hyperopia.

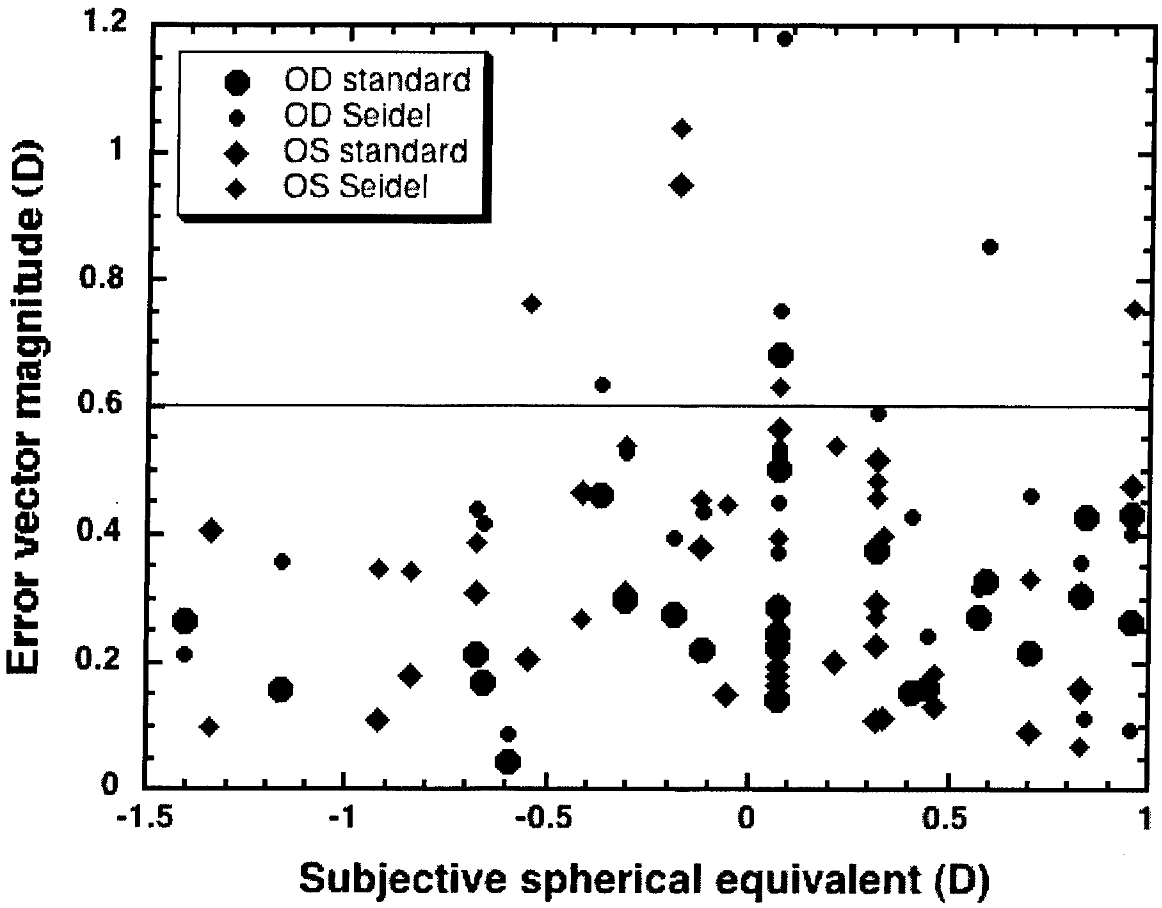


Figure 4. Distribution of COAS refractive vector errors (with cycloplegia). Approximately 90% of the errors, using both the standard sphere (large symbols) and Seidel sphere (small symbols) are within 0.60 D.

For comparison, Figure 5 shows a similar analysis for the autorefractor errors. The distribution of errors is generally similar to those of the COAS, perhaps marginally better than the COAS without cycloplegia and marginally worse than the COAS with cycloplegia. Cycloplegia did not significantly improve the error distribution for the autorefractor. About 80% of the errors were less than 0.60 D. The autorefractor measured across a 3.5-mm diameter pupil.

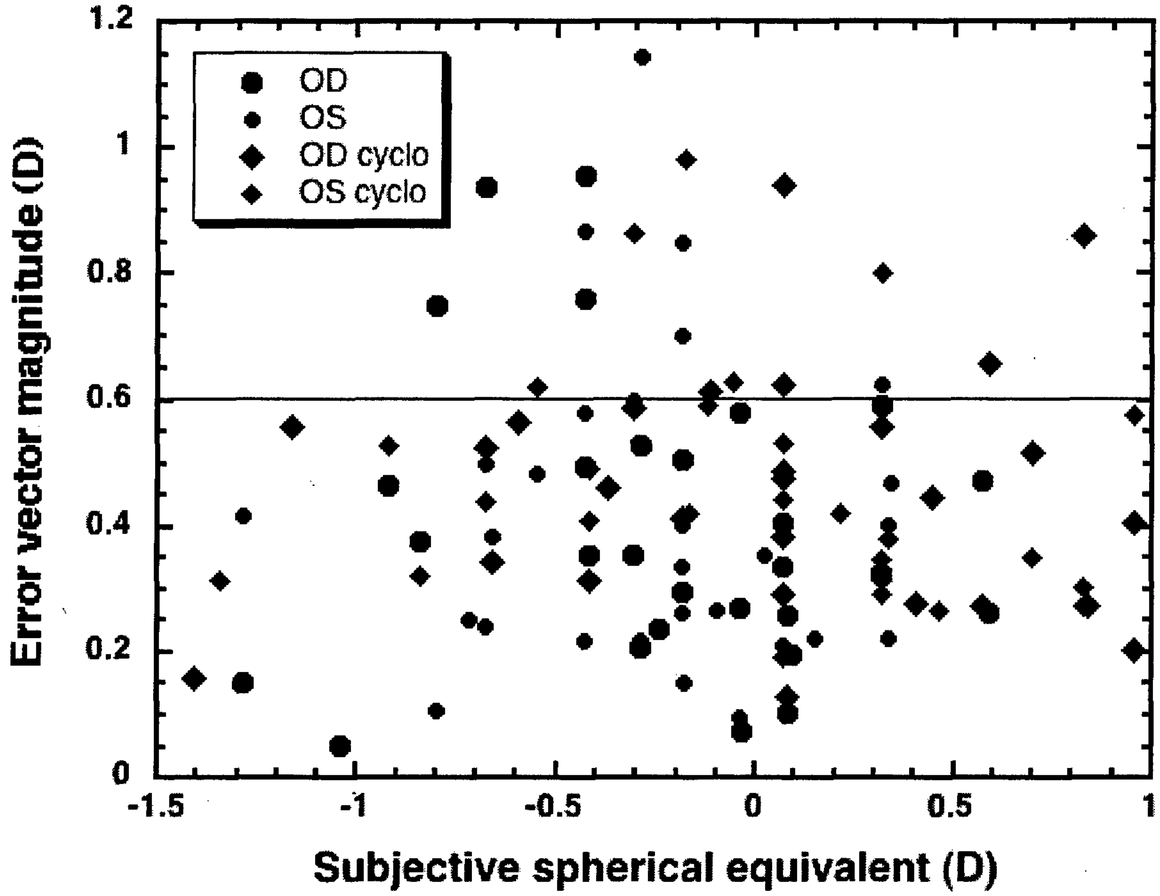


Figure 5. Distribution of autorefractor refractive vector errors. Errors for right and left eyes are shown when measured without (circles) and with (diamonds) cycloplegia. Without cycloplegia, 84% of the errors were less than 0.60 D. With cycloplegia, about 80% of the errors were less than 0.60 D.

Repeatability

Table 5 shows repeatability of the COAS for five measurements taken within about one minute. Repeatability is quantified using the coefficient of repeatability, which was described in the methods section. For comparison, repeatability coefficients for the autorefractor are also listed in Table 5 (three measurements). The autorefractor's repeatability coefficients were about 0.1 D smaller than those of the COAS.

Table 5.
COAS lower-order repeatability.

Eye/condition	COAS standard sphere (D)	COAS Seidel sphere (D)	Autorefractor (D)
OD/ no cyclo	0.20	0.24	0.12
OS/ no cyclo	0.18	0.23	0.20
OD/ cyclo	0.12	0.18	0.08
OS/ cyclo	0.18	0.22	0.09

Note: Values are shown for the standard and Seidel options for computing spherical power, as well as for autorefraction. Analysis pupil diameter was 5.0 mm.

Figure 6 shows COAS repeatability for higher-order aberrations. Data points indicate repeatability in terms of the mean 95% confidence intervals for each eye/condition for each mode. Approximately 90% of the points fall within the shaded region, which generalizes mode-by-mode repeatability based on these results. That is, COAS repeatability for each mode is indicated by the height of the shaded regions (in μm), which declines in each successive order. The respective values for the third, fourth, fifth, sixth and sevenths orders are: 0.035, 0.025, 0.02, 0.015 and 0.010 μm. Eighth-order values (not shown) were similar to those in the seventh order. These values can be interpreted as our estimate of measurement noise; that is, variability caused by the instrument or measurement procedure.

Instrument myopia

Instrument myopia had little effect on astigmatism (less than 0.1 D change in each case), so we summarized instrument myopia in terms of the spherical equivalent power (Table 6). COAS instrument myopia was smaller when the default sphere was used, about –0.25 D. For comparison instrument myopia with the autorefractor was about –0.2 D.

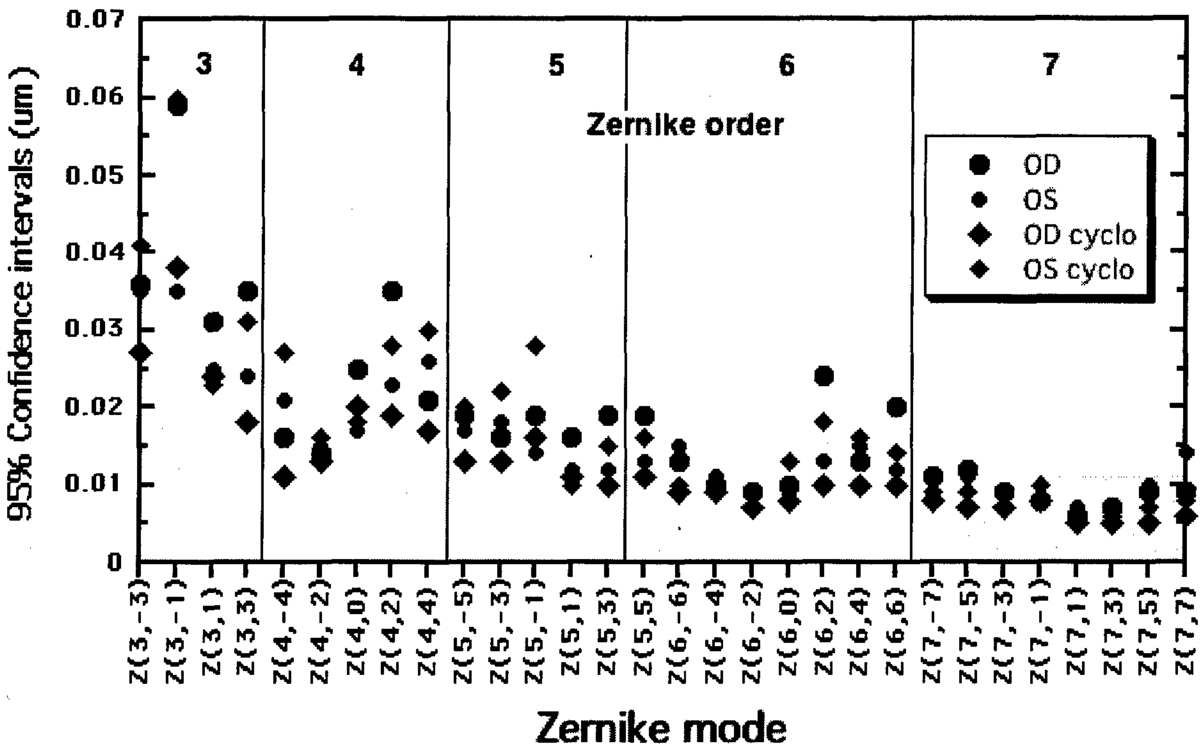


Figure 6. COAS higher-order repeatability. The shaded region contains 90% of the data points and indicates a generalized estimate instrument noise for each mode. Pupil diameter was 5.0 mm.

Discussion

Aberrometers, such as the COAS, provide the only means for measuring higher-order aberrations in a clinical setting, and the COAS was chosen by USAARL to study the ocular aberrations of Army pilots. Before scientists or doctors can depend on the data provided by aberrometers, they need to know how reliable these instruments are. Since aberrometers measure lower-order aberrations as well, they can also function as autorefractors that estimate a patient's spectacle prescription. We assessed COAS accuracy, repeatability and instrument myopia for lower-order aberrations and only repeatability for higher-order aberrations. All COAS analysis was done for a 5.0-mm diameter pupil.

Table 6.
Instrument myopia for the COAS and autorefractor.

Instrument	Eye	Sphere method	Inst myopia (D)
COAS	OD	standard	-0.24 ±0.42
COAS	OS	standard	-0.24 ±0.35
COAS	OD	Seidel	-0.36 ±0.43
COAS	OS	Seidel	-0.29 ±0.41
Autorefractor	OD	NA	-0.19 ±0.33
Autorefractor	OS	NA	-0.19 ±0.37

Note: Values show instrument myopia in terms of spherical equivalent power with standard deviations. A negative value indicates that, on average, the instrument showed more myopia (less hyperopia), than the true distance refractive error.

Accuracy

We expressed accuracy for measuring the combined lower-order aberrations of sphere and astigmatism by the magnitude of the mean error vector. COAS accuracy was best with the default sphere and cycloplegia—0.3 D by this statistic (Table 3). The autorefractor's best accuracy was 0.4 D (Table 4), but this was found without cycloplegia. To put this into perspective, a 0.3-D error vector magnitude is equivalent to a 1/8-D error in both the sphere and cylinder combined with a 12-degree axis error. This would be considered a very small error clinically. Most spectacle prescriptions are written in 0.25 D power increments, because it is difficult to subjectively measure spherical or astigmatic refractive error with an accuracy of less than 0.25 D. Thus, we found that, on average, the COAS was capable of the same level off accuracy we can expect for a conventional clinical subjective refraction. In some cases, however, COAS and autorefractor error vector magnitudes of about 1.0 D (Figures 2-4), which is equivalent to a 0.5-D error in both the sphere and cylinder with a 30-degree axis error. Our results with human eyes were only marginally worse than the COAS' reported accuracy with model eyes. Cheng (2003) reported mean errors of ±0.1 D sphere, ±0.1D cylinder and ±2° axis (equivalent to a 0.16-D vector error) across a broad range of refractive errors (-4.00 to +3.00 D) on model eyes. Accuracy declined slightly for greater refractive errors in that study.

There is still debate among vision scientists about how to best estimate the clinical subjective sphere from aberrometer data. The COAS standard setting computes the sphere directly from the second-order aberration Z_2^0 (defocus), while the Seidel-sphere option takes into account the fourth-order aberration Z_4^0 (spherical aberration). Some scientists believe that the Seidel sphere should give a better estimate of the subjective sphere, especially with large pupils. When no cycloplegia was used, we did not find better accuracy with the Seidel sphere. With cycloplegia it was marginally worse than with the default sphere. It's possible that our pupil diameters (5.0 mm) were not large enough to benefit from the Seidel computation, since, in another study, we found slightly better accuracy in larger pupils with the Seidel sphere (Salmon et al., 2003). It

appears therefore that users should normally leave the standard sphere setting in place but consider using the Seidel option for widely dilated (>6 mm) pupils.

As mentioned in the Methods section, we were not able to evaluate accuracy for higher-order aberrations in this study. Cheng (2003) measured COAS accuracy for some higher-order modes using model eyes, for which the higher-order aberrations could be computed by ray-tracing She found mean errors of <0.01 μm for Z_4^0 (spherical aberration), <0.03 for Z_3^1 (coma) and $\leq$ 0.3 μm for Z_4^2 (5.0-mm pupil). These correspond to the respective equivalent diopter values of 0.1, 0.3 and 0.3 D (Thibos et al., 2002).

Repeatability

Repeatability refers to the variability of repeated measurements. The COAS repeatability coefficients for lower-order aberrations (< 0.25 D) were similar to what we would expect from a normal clinical subjective refraction. Since COAS repeatability was marginally better with the default sphere (mean 0.17 D), we recommend using it rather than the Seidel sphere when trying to optimize repeatability.

We also evaluated COAS repeatability for higher-order aberrations. Higher-order repeatability was generally the same with or without cycloplegia. As shown by the shaded region in Figure 5, it was approximately 0.035 μm (equivalent to 0.04 D) for third-order modes, 0.025 μm (0.03 D) for fourth-order modes and declined to <0.02 μm (0.02 D) for the fifth order and above. These values are important to keep in mind when interpreting aberrometry, because Zernike coefficients less than the noise level are essentially unmeasurable. For example, if the instrument reports –0.02 μm of mode Z_3^{-1} (vertical coma) aberrations, one may not assume that the patient has any of this aberration, since it could just be due to instrument noise. These results apply for a pupil diameter of 5.0 mm. Noise would increase with larger pupils and decrease with smaller pupils.

The variability that we measured for higher-order aberrations was only slightly worse that that reported by Cheng et al. (2004) They estimated that most of the COAS' variability was attributable to fluctuations in accommodation, the tear film or eye position rather than due to the instrument itself. The COAS may be subject to axial, transverse or angular positioning errors, but they demonstrated that, within the range of misalignments expected for normal clinical use, these caused no significant error.

Instrument myopia

The COAS induced marginally more instrument myopia than the autorefractor (mean 0.28 versus 0.19 D). We previously found almost no instrument myopia with the COAS, but all of those subjects were myopic (Salmon et al., 2003). The slightly greater instrument myopia in this study may have been caused by the inclusion of young hyperopes, who tend to over-accommodate habitually.

Conclusions

In normal eyes higher-order aberration are very small and have little effect on vision. The magnitudes of higher-order aberrations in normal eyes (averaged across several studies), for 5.0- and 6.0-mm pupils, are shown in Figure 7 (Salmon & van de Pol, 2004). The figure also shows the noise range we determined for a 5.0-mm pupil. For a 5.0-mm pupil, the most prominent aberrations—all third-order modes and fourth-order mode Z_4^0 (spherical aberration)—are measurable by the COAS since they exceed measurement noise (shaded zone). However, for a 5.0-mm pupil, the other fourth-order and fifth-order aberrations are so small that they don't exceed the noise limits, and would therefore be difficult to measure. In order to detect the subtle aberrations in an eye with good optics, we therefore recommend measuring with as large a pupil as possible. Clinicians, however, are primarily interested in measuring abnormal aberrations, which would be larger than the mean values plotted in Figure 7. Based on this analysis, all problematic aberrations should be easily measurable with the COAS. This is particularly relevant for refractive surgery or in other cases of subnormal vision caused by poor optics.

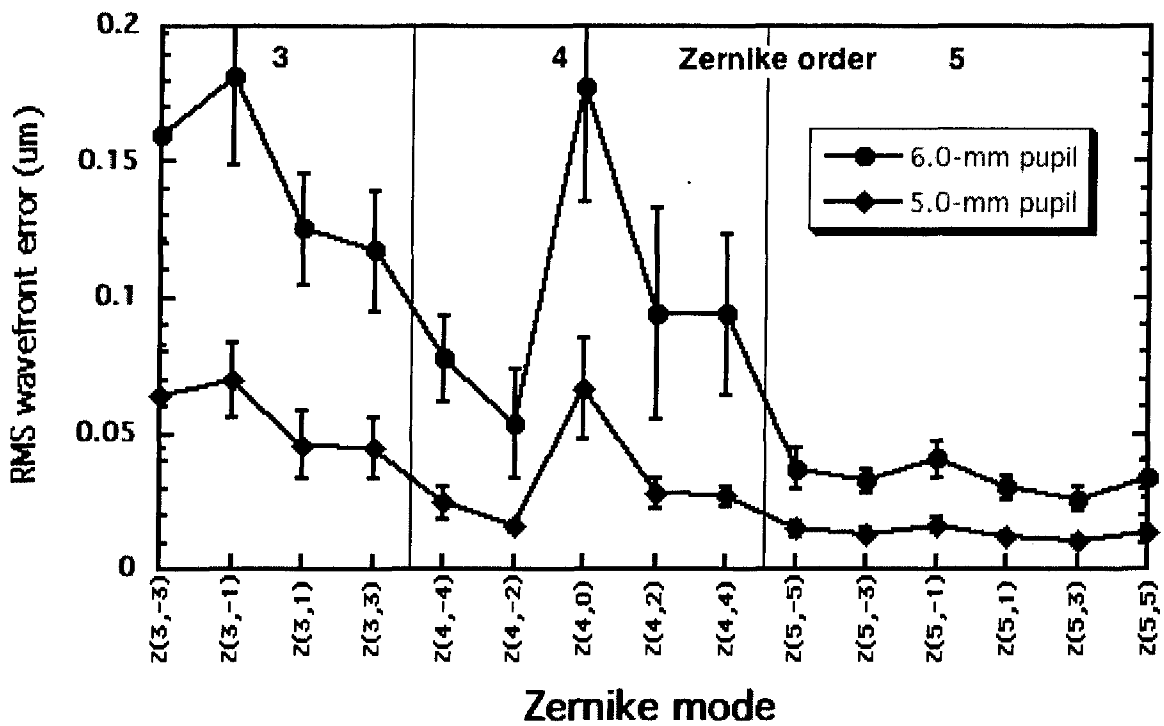


Figure 7. Magnitude of normal higher-order aberrations. Mean values expected for normal eyes with 5.0 and 6.0-mm diameter pupils (Salmon & van de Pol, 2004).

In addition to its capacity to measure higher-order aberrations, the COAS can serve as an autorefractor by measuring sphere and astigmatism. Like a conventional autorefractor, it occasionally has larger-than-average measurement errors, so when accuracy is critical, we recommend comparing COAS refractions to that obtained by a careful subjective refraction. We recommend using the standard rather than the Seidel sphere setting, except for very large pupils. Cycloplegia slightly improves accuracy and repeatability for measuring sphere and astigmatism,

but it is important to note that cycloplegia itself can change the aberrations slightly (Carkeet, 2003). Finally, we conclude that the COAS aberrometer provides scientists and clinicians with an accurate and repeatable way to objectively measure lower- and higher-order aberrations of eyes.

References

Atchison, D., Scott, D., & Cox, M. (2000). Mathematical Treatment of Ocular Aberrations: a User's Guide. *Vision Science and Its Applications,* 35 (pp. 110-130). Santa Fe, NM: Optical Soc Am.

Bland, J., & Altman, D. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *The Lancet, 1*, 307-310.

Boxer Wachler, B.S. (2003). Effect of pupil size on visual function under monocular and binocular conditions in LASIK and non-LASIK patients. *J Cataract Refract Surg, 29* (2), 275-278.

Boxer Wachler, B.S., Huynh, V.N., El-Shiaty, A.F., & Goldberg, D. (2002). Evaluation of corneal functional optical zone after laser in situ keratomileusis. *J Cataract Refract Surg, 28* (6), 948-953.

Carkeet, A.V., S; Tan, Y.K.; Lee, D.Y.J.; Tan, D.T.H. (2003). Higher Order Ocular Aberrations After Cycloplegic and Non-cycloplegic Pupil Dilation. *J Ref Surg, 19* (May/June), 316-322.

Casson, E.J., Jackson, W.B., Mintsioulis, G., Norton, S., Munger, R., Strolenberg, U. (1996). Visual Performance under Dilated Conditions Following Excimer Photorefractive Keratectomy. *Vision Science and its Applications* (pp. 222-225). Santa Fe, NM.

Cheng, X., Himebaugh, N., Kollbaum, P., Thibos, L., & Bradley, A. (2003). Validation of a clinical Shack-Hartmann aberrometer. *Optom Vis Sci, 80* (8), 587-595.

Cheng, X., Himebaugh, N., Kollbaum, P., Thibos, L., & Bradley, A. (2004). Test-retest reliability of clinical Shack-Hartmann measurements. *Invest Ophthalmol Vis Sci, 45* (1), 351-360.

Fugate, R., & Wild, W. (1994). Untwinkling the stars - part I. *Sky & Telescope, 1994* (May)

Hamam, H. (2000). A Quick Method for Analyzing Hartman-Shack Patterns: Application to Refractive Surgery. *J Ref Surg, 16* (Sept/Oct), S636-S642.

Haw, W.W., & Manche, E.E. (2001). Effect of preoperative pupil measurements on glare, halos, and visual function after photoastigmatic refractive keratectomy. *J Cataract Refract Surg, 27* (6), 907-916.

Hofer, H., Artal, P., Singer, B., Aragon, J., & Williams, D. (2001). Dynamics of the eye's wave aberration. *J Opt Optom Assoc, 18* (3), 497-506.

Howland, H. (2000). The History and Methods of Ophthalmic Wavefront Sensing. *J Ref Surg, 16* (5), S552-S553.

Lee, Y.C., Hu, F.R., & Wang, I.J. (2003). Quality of vision after laser in situ keratomileusis. Influence of dioptric correction and pupil size on visual function. *J Cataract Refract Surg, 29* (4), 769-777.

Liang, J., Grimm, B., Goelz, S., & Bille, J.F. (1994). Objective measurement of wave aberrations of the human eye with the use of a Hartmann-Shack wave-front sensor. *J Opt Soc Am A, 11* (7), 1949-1957.

Liang, J., & Williams, D.R. (1997). Aberrations and retinal image quality of the normal human eye. *J Opt Soc Am A, 14* (11), 2873-2883.

Liang, J., Williams, D.R., & Miller, D.T. (1997). Supernormal vision and high-resolution retinal imaging through adaptive optics. *J Opt Soc Am A, 14* (11), 2884-2892.

Maguire, L. (1994). Keratorefractive Surgery, Success and the Public Health. *Am J Ophthalmol, 117*, 394-398.

Marcos, S., Diaz-Santana, L., Llorente, L., & Dainty, C. (2002). Ocular aberrations with ray tracing and Shack-Hartmann wave-front sensors: Does polarization play a role? *J Opt Soc Am A, 19* (6), 1063-1072.

Martínez, C.E., Applegate, R.A., Klyce, S.D., McDonald, M.B., Medina, J.P., & Howland, H.C. (1998). Effect of pupillary dilation on corneal optical aberrations after photorefractive keratectomy [see comments]. *Archives of Ophthalmology, 116* (8), 1053-1062.

Miller, D. (2000). Retinal Imaging and Vision at the Frontiers of Adaptive Optics. *Physics Today, 53* (1), 31-36.

Moreno-Barriuso, E., & Navarro, R. (2000). Laser Ray Tracing versus Hartmann-Shack sensor for measuring optical aberrations in the human eye. *J Opt Soc Am, 17* (6), 974-984.

Platt, B., & Shack, R. (2001). History and Principles of Shack-Hartmann Wavefront Sensing. *J Ref Surg, 17* (Sept/Oct), S573-S577.

Porter, J., Guirao, A., Cox, I., & Williams, D.R. (2001). Monochromatic aberrations of the human eye in a large population. *J Opt Soc Am A, 18* (8), 1793-1803.

Prieto, P., Vargas-Martin, F., Goelz, S., & Artal, P. (2000). Analysis of the performance of the Hartmann-Shack sensor in the human eye. *J Opt Soc Am A, 17* (8), 1388-1398.

Rosenfield, M., & Chiu, N.N. (1995). Repeatability of subjective and objective refraction. *Optom Vis Sci, 72*, 577-579.

Salmon, T. (1999). Corneal Contribution to the Wavefront Aberration of the Eye. *School of Optometry* (p. 208). Bloomington, IN: Indiana University.

Salmon, T., & Thibos, L. (1998). Comparison of the eye's wave-front aberration measured psychophysically and with the Shack-Hartmann wave-front sensor. *J Opt Soc Am A, 15* (9), 2457-2465.

Salmon, T., & van de Pol, C. (2004). Zernike Coefficient Norms—Comparison of Studies. *American Academy of Optometry annual meeting,* 81 (p. s). Tampa, FL.

Salmon, T., & West, R. (2002). Optical wavefront sensing of the human eye. In: S. Pandalai (Ed.) *Recent Research Developments in Optics,* 2 (Trivandrum, Kerala, India: Research Signpost.

Salmon, T.O., Rash, E., Mora, J., & Reynolds, B. (2002). Detecting Corneal Anomalies in Potential Army Aviators. *US Army Med Dept J,* (Jan-Mar)

Salmon, T.O., West, R.W., Gasser, W., & Kenmore, T. (2003). Measurement of Refractive Errors in Young Myopes Using the COAS Shack-Hartmann Aberrometer. *Optom Vis Sci, 80* (1), 6-14.

Thibos, L., Applegate, R., Schwiegerling, J., Webb, R., & Members, V.S.T. (2000). Standards for Reporting the Optical Aberrations of the Eye. *Vision Science and Its Applications,* 35 (pp. 232-244). Santa Fe, NM: Optical Soc Am.

Thibos, L., & Hong, X. (1999). Clinical Applications of the Shack-Hartmann Aberrometer. *Optom Vis Sci, 76* (12), 817-825.

Thibos, L., Hong, X., Bradley, A., & Cheng, X. (2002). Statistical Variation of Aberration Structure and Image Quality in a Normal Population of Healthy Eyes. *J Opt Soc Am A, 19* (12), 2329-2348.

Thibos, L.N., Wheeler, W., & Horner, D. (1997). Power vectors: an application of fourier analysis to the description and statistical analysis of refractive error. *Optom Vis Sci, 74*, 367-375.

Wachler, B.S., Durrie, D.S., Assil, K.K., & Krueger, R.R. (1999). Role of clearance and treatment zones in contrast sensitivity: significance in refractive surgery. *J Cataract Refract Surg, 25* (1), 16-23.

Walline, J.J., Kinney, K.A., Zadnik, K., & Mutti, D.O. (1999). Repeatability and validity of astigmatism measurements. *J Ref Surg, 15*, 23-31.

Yoon, G.Y., & Williams, D.R. (2002). Visual performance after correcting the monochromatic and chromatic aberrations of the eye. *J Opt Soc Am A, 19* (2), 266-275.

Zadnik, K., Mutti, D.O., & Adams, A.J. (1992). The repeatability of measurement of the ocular components. *Invest Ophthalmol Vis Sci, 33*, 2325-2333.